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# Geomorphological characterization, spatial distribution and environmental status assessment of coralligenous reefs along the Latium continental shelf

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ABSTRACT

Coralligenous reefs are typical underwater seascapes of the Mediterranean Sea and are ranked among the most relevant ecosystems of the basin and a pole of biodiversity. For their critical importance for ecosystems conservation, coralligenous reefs are included among the indicators that should be assessed under the Marine Strategy Framework Directive (MSFD). However, information regarding their spatial distribution and the influence of environmental factors on their structure and biological characteristics is still poor. As part of monitoring regional programs for the implementation of the MSFD in Italy, an extensive study was performed along the Latium continental shelf, aimed to define and map the distribution of coralligenous reefs and to assess their environmental status in three different study areas, characterized by different environmental conditions and subjected to different potential levels of human pressure. For each area, a large dataset was collected, including multibeam bathymetry, side scan sonar records and ROV video transects. The integrated analysis of geophysical data and ROV videos allowed to identify the morpho-acoustic facies indicative of coralligenous outcrops and to map their distribution across the study areas. In parallel, a quantitative analysis of video transects was carried out, in order to characterize the megabenthic communities in terms of species composition, abundance, health status of structural species, and to evaluate the abundance of marine litter. The environmental status of the coralligenous communities was then assessed through the application of the Mesophotic Assemblages Conservation Status (MACS) index.

The results obtained showed a large variability in the distribution and characteristics of coralligenous reefs and associated assemblages along the Latium continental shelf, likely reflecting the different environmental conditions and human pressure in the different areas. Coralligenous reefs were reported from all the investigated areas, hosting a rich and varied associated fauna with dense gorgonian forests, also featuring species of relevance for conservation such as *Corallium rubrum*. The application of MACS index allowed to distinguish among a wide range of ecological conditions of the coralligenous communities, spanning from high to poor environmental status across different sites. The assessment of the extent and diversity of coralligenous assemblages through the combination of geomorphological analysis, acoustic mapping and quantitative video analysis represents an efficient tool, which may help governments and stakeholders making informed management decisions for future coastal planning and conservation strategies.

## 1. Introduction

The endemic biogenic reefs known as "coralligenous" are typical underwater seascapes of the Mediterranean Sea and have been recognized as the second pole of species diversity, after *Posidonia oceanica* meadows (Boudouresque, 2004; Ballesteros, 2006). Coralligenous reefs are primarily formed by carbonate deposition of encrusting coralline algae growing in dim light conditions and to a lesser extent by bioconstructor animals including polychaetes, sponges, bryozoans, and anthozoans (Pérès & Picard, 1964; Ballesteros, 2006; Bellan-Santini

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et al., 2007). The building activity of algal and animal constructors is counterbalanced by physical as well as biological eroding processes, resulting in complex three-dimensional structures that represent an attractive habitat for the settlement, feeding, spawning and shelter of a large variety of marine species (Ballesteros, 2006; Relini et al., 2009). Because of their extent, associated biodiversity, production and role in carbon regulation (Piazzi et al., 2009; Martin et al., 2013; Martin et al., 2014), coralligenous is ranked among the most valuable ecosystems in the Mediterranean Sea and is regarded as an important source of ecosystem services (Zunino et al., 2019).

The architecture, structure and depth range of coralligenous reefs, as well as their specific composition, can vary at both geographical and local scale according to the different environmental factors and the geomorphology of the area (Ponti et al., 2011; Casas-Güell et al., 2015; Piazzi et al., 2019; Valisano et al., 2019). Two main categories have been traditionally described: i) rims, growing on vertical or sub-vertical cliffs or surrounding the opening of marine caves and ii) banks, developing on horizontal continental shelves over consolidated sediments, coalesced rhodoliths or pre-existing rocky outcrops (Pérès & Picard, 1964; Laborel, 1987; Ballesteros, 2006). The integration of seafloor imagery systems such as multibeam echosounders (MBES) and side scan sonars (SSS), with underwater photo and video imagery, allowed to recognize a larger variability of coralligenous reef morphologies (Casellato & Stefanon, 2008; Bracchi et al., 2015), together with a marked heterogeneity in their spatial distribution and biological characteristics (Cánovas Molina et al., 2011; Zapata-Ramírez et al., 2013). However, the role of geomorphological and environmental factors on the distribution of coralligenous reefs and the characteristics of associated fauna is still far to be fully understood.

Similarly to many other coastal systems, coralligenous are increasingly suffering impacts of a large range of anthropogenic disturbances related to fishing activities, pollution and littering, change in land use and altered sedimentation, introduction of alien species and climate change (Piazzi et al., 2012; Salomidi et al., 2012; Bevilacqua et al., 2018). The low recruitment rates, high longevity and persistence of sessile species structuring the reefs (Teixidó et al., 2011), make them particularly vulnerable to human impacts, particularly those caused by fishing activities. Fishing gears and lines can damage fauna, especially the large erect and branched organisms, by causing accidentally eradication, breakage of ramifications and tissue abrasion, which may favour epibionts covering and necrosis (Angiolillo et al., 2015; Ferrigno et al., 2017a; Consoli et al., 2019; Enrichetti et al., 2019a). The increase in turbidity and sedimentation produced by bottom trawling over nearby sediments can also affect coralligenous communities (Linders et al., 2018). Furthermore, as coralligenous reefs are constituted by many calcareous organisms, they are sensitive to climate changes and ocean acidification, often acting simultaneously to other anthropogenic pressures, and therefore especially threatened at global scale (Steller et al., 2007; Zunino et al., 2019; Ceccherelli et al., 2020; Gómez-Gras et al., 2021).

The ecological relevance of coralligenous reefs and the pervasive range of impacts threatening them have driven efforts in their safeguard and conservation through international agreements (Giakoumi et al., 2013). Coralligenous reefs have been identified as Mediterranean priority habitats by the EU Habitats Directive and included in the network of Natura 2000 sites (92/43/CE). An Action Plan for the conservation of the coralligenous and other calcareous bioconcretions in the Mediterranean Sea was established in the framework of the Barcelona Convention (UNEP-MAP-RAC/SPA, 2008). Coralligenous reefs are also crucial elements for several descriptors defined by the Marine Strategy Framework Directive (MSFD, 2008/56/EC) to evaluate the reaching and/or maintain of the Good Environmental Status (GES) of European marine waters, specifically Descriptor 1 biodiversity, Descriptor 6 seafloor integrity and Descriptor 10 marine litter.

Nevertheless, the paucity of detailed cartographic information on the small-scale distribution of this ecosystem, as well as of standardized and comparable information on the ecological status of its communities, represent important knowledge gaps for the development of efficient management and conservation plans (UNEP-MAP-RAC/SPA, 2008; Pergent, 2011; Çinar et al., 2020).

In the last decade, several methods and indices have been developed to assess the ecological quality of coralligenous assemblages through non-destructive approaches, such as the Coralligenous Assemblage Index (CAI) (Deter et al., 2012), the COralligenous Assessment by ReefScape Estimate (COARSE) (Gatti et al., 2015), the Ecological Status of Coralligenous Assemblages (ESCA) (Piazzi et al., 2015; Piazzi et al., 2021) and the Coralligenous Bioconstructions Quality Index (CBQI) (Ferrigno et al., 2017b). Recently, the Mesophotic Assemblages Conservation Status (MACS) index has been developed for a large-geographic environmental status assessment of mesophotic temperate reefs, including coralligenous assemblages (Enrichetti et al., 2019b). The index combines two independent status and impact indicators following a DPSIR (Driving forces – Pressures – Status – Impacts – Response) approach (Elliott et al., 2017) and defines the environmental status as the outcome of the biocoenotic complexity of benthic communities plus the amount of impacts upon them (Enrichetti et al., 2019b). The MACS index has been already tested on several temperate mesophotic reefs of the Ligurian and Tyrrhenian seas (Enrichetti et al., 2019b) and has the potential to be applied on a large geographic scale, since it relies on metrics derived from the Italian MSFD protocol (MATTM-ISPRA, 2019) for monitoring mesophotic coralligenous and rocky reefs, therefore collected at a national level.

As part of monitoring regional programs for the implementation of the MSFD in Italy, an extensive study was performed in three areas along the Latium continental shelf (Central Tyrrhenian Sea), aimed to define and map the distribution of coralligenous reefs and to assess their environmental status. The study areas include a submarine rocky promontory (i.e. Capo Linaro), an isolated shoal along the outer shelf (i.e. Costacuti) and an insular shelf dominated by carbonate sedimentation (i.e. Palmarola Island, western Pontine Archipelago). Such distinct settings can be considered as representative of the variability of environmental conditions (in terms of geological setting and sedimentation rates, hydrodynamism, water transparency) occurring along the Latium region, and subjected to different potential levels of human pressure. For each area, a large dataset is available including multibeam bathymetry, side scan sonar records and ROV videos. The integrated analysis of high-resolution morphoacoustic data and ROV video images offers the opportunity to evaluate how the different geomorphological, environmental conditions and human pressures in the study areas may reflect on the variability of coralligenous reefs and associated communities. The aims of this paper are therefore: i) to define and map the distribution of coralligenous reefs in the study areas ii) to characterize their geomorphology and associated benthic communities and iii) to assess their environmental status through the estimation of MACS index.

## 2. Material and methods

### 2.1. Study areas

The study areas are located along the Latium continental shelf, in the central Tyrrhenian Sea, to the north and to the south of the Tiber River's mouth (Fig. 1). The sites were selected based on the possible occurrence of the habitat of interest, as suggested by previous observations, literature data or geomorphological seafloor characteristics. Furthermore, the study areas were chosen to be representative of the variability of environmental conditions occurring along the Latium region.

The Latium continental shelf is located on a young (<10 My) passive margin related to the opening of the back-arc Tyrrhenian Sea associated with the eastward "rollback" of a west dipping subduction zone (Doglioni et al., 2004). The shelf has an average width of 20 km, and widens to 30–40 km to the north of Capo Linaro and to the south of Capo Circeo Promontory, respectively (Fig. 1). The mean gradients of the shelf

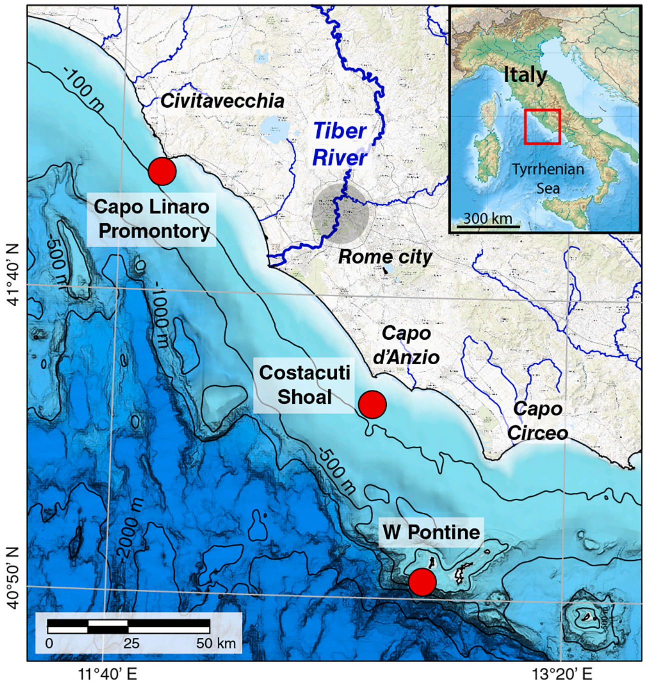


**Fig. 1.** Shaded relief map and isobaths of the Latium continental margin (Central Tyrrhenian Sea) with location of the study areas. Bathymetry downloaded from EMODNET portal (*https://portal.emodnet-bathymetry.eu/*). The blue lines represent the drainage network on land.

are about 0.4° and the shelf break is located at about 120–130 m depth (Selli, 1970). In the central sector of Latium region between Capo Linaro and Capo d'Anzio, the physiography and sediment dynamics of the shelf are greatly influenced by the presence of Tiber River (Chiocci & La Monica, 1996), the second largest river in Italy. Tiber River is about 409 km long, has a mean annual discharge of about 225 $m^3$/s, with annual peaks exceeding 1500 $m^3$/s (Iadanza & Napolitano, 2006), debouching in the Tyrrhenian Sea close to the city of Rome. Smaller rivers draining volcanic reliefs are present in the northern sector of the region, while in the southern sectors terrigenous inputs are more limited because of the lack of major rivers and the occurrence of coastal lakes (Chiocci & La Monica, 1996). In the southern sector of the Latium continental margin, the extensional tectonic deformations led to the creation of a NE-SW morpho-structural high (Malinverno & Ryan, 1986), about 35 km off the Italian peninsula, where three main volcanic islands (i.e., Palmarola, Ponza, and Zannone, belonging to the western Pontine Archipelago) formed during the Plio-Pleistocene (4.5–1.0 Ma, Cadoux et al., 2005).

The general oceanographic circulation over the continental shelf involves the northward flow of Tyrrhenian surface waters (Modified Atlantic Waters, MAW, Pinardi & Masetti, 2000), which is locally modified in correspondence of the western Pontine morpho-structural high. Surface geostrophic currents show a marked seasonal variability, being more energetic in winter than in summer (Astraldi & Gasparini, 1992). Surface salinity ranges from 36.8 to 38.5 psu and surface water temperatures seasonally range between 13 °C and 24 °C (La Violette, 1994). This sector of the Tyrrhenian Sea is characterized by a microtidal regime with predominant storms from the west (Corsini et al., 2004).

#### 2.1.1. Capo linaro promontory

Capo Linaro Promontory, in the northern Latium about 40 km north of the Tiber River's mouth, is characterized by coastal cliffs mainly made up by shales and marly calcareous, arenaceous turbidites of Meso-Cenozoic age (Bartole, 1990). As a consequence, the morphology of the inner shelf is uneven, with a prevalent rocky seafloor colonized by sparse patches of *Posidonia oceanica* seagrass and, starting from about 15 m depth, by coralligenous communities (Nascetti & Martino, 2009; Ardizzone et al., 2018). The area of Capo Linaro is still influenced by the sediment input from Tiber River, whose suspended sediment plume is mainly transported northward by littoral and geostrophic currents (Chiocci & La Monica, 1996; Pitarch et al., 2019). The area is also characterized by a very large port (Port of Civitavecchia), about 5 km north of the Capo Linaro Promontory, and by coastal human settlements (Santa Marinella and Civitavecchia towns).

#### 2.1.2. Costacuti shoal

Costacuti Shoal is an isolated shoal located about 40 km off the coasts of Capo d'Anzio Promontory, in the southern Latium. The shoal is about 250 m wide and 1600 m long, oriented in a NW-SE direction; it rises about 10 m from the surrounding seafloor, between 48 and 36 m depth (Nonnis et al., 2002). The rocky shoal is characterized by the presence of *Posidonia oceanica* meadows, coralligenous reefs and maërl beds, these latter extending also in the surrounding shelf sectors (Nicoletti et al., 2003). Dredging activities for the exploitation of a relict sand deposit aimed at beach nourishment have been carried out from 1999 to 2007 in three sites about 1.5 km far from the shoal (Nonnis et al., 2011). A heavily exploited trawling fishing ground is also present offshore the coasts of Anzio, where the homonymous port is located (Corsi, 1998).

#### 2.1.3. Palmarola insular shelf

The insular shelf surrounding Palmarola Island is characterized by an irregular seafloor due to the presence of volcanic outcrops, biogenic build-ups, erosional escarpments and fluid escape features (Ingrassia et al., 2015; Martorelli et al., 2016). Because of the lack of significant river runoff from the islands and the large distance to the mainland, the seafloor is mainly covered by bioclastic sands (e.g., foraminifera, coralline algae, bryozoans, ostracods, sponge spicules) with subordinate terrigenous sediments (Martorelli et al., 2012). The low siliciclastic input also enhances the transparency of the water column, allowing the development of varied and rich benthic communities encompassing *Posidonia oceanica* meadows, coralligenous reefs and rhodolith beds (Martorelli et al., 2012; Ardizzone et al., 2018; Ingrassia et al., 2019; Sañé et al., 2021). A relative low anthropogenic impact has been observed in this area (Ingrassia et al., 2019), likely due to the distance for the mainland and the absence of large human settlement.

### 2.2. Geophysical data

Geophysical data include high-resolution bathymetry from multibeam echosounders and side-scan sonar data.

In the Capo Linaro area, data were collected in 2016 using a Reson SeaBat T50-P multibeam system (400 kHz) and an Edgetech 4125 side scan sonar (600 kHz). In the Costacuti area, data were collected during December 2017 with a multibeam echosounder Reson SeaBat 8125 system (455 kHz) and with a Klein 3900 side scan sonar (445 kHz). In the Palmarola area, bathymetric data were collected in 2009 with a Kongsberg EM 3002D multibeam system (300 kHz) on board the R/V Mariagrazia during the research cruise MagicIgag10/09, while side scan sonar data were acquired during December 2017 with a Klein 3900 sonar (445 kHz). Data positioning was achieved using Differential GPS, while Real-Time Kinematic positioning was supplied only for Capo Linaro area.

Processing of raw data was performed to produce Digital Elevation Models (DEMs) of the three study areas with a cell size of 2 m and mosaics of backscatter intensity with 0.2 m resolution.

The analysis of bathymetric data and backscatter mosaics allowed to identify the morpho-acoustic facies potentially indicative of coralligenous outcrops, where ROV video transects were then carried out to confirm the presence of this ecosystem and to assess its environmental status.

*2.2.1. ROV videos acquisition and analyses*

ROV surveys were conducted between February 2017 and January 2018 on board small vessels. Video footages in the Capo Linaro area were obtained by means of the ROV Falcon, equipped with a low resolution navigation camera and a high-resolution GoPro camera. In Costacuti and Palmarola areas the ROV Pollux III (Global Electric Italiana) was used, equipped with a Sony CCD 1/3″ navigation camera, a Sony HDRCX115E high-definition camera and a GoPro camera. During all surveys, the ROVs were equipped with laser pointers (with a laser beam spacing of 20 cm) to provide references for scale, and an ultra-short baseline positioning system to ensure detailed records of the ROV tracks, with a maximum estimated error of $\pm$ 2 m. USBL data were post-processed with manual removal of out of-sequence beams and spikes and smoothing of the navigation tracks.

From five to eight ROV dives of variable length (280 to 1065 m) were performed in each area (Fig. 2, Table 1). Sampling strategy was aimed at exploring three different sites for each area; sites were selected as being representative of the diverse seabed morphologies and acoustic facies potentially associated with coralligenous outcrops, revealed during the geophysical surveys.

In order to estimate the distribution of coralligenous reefs across the study areas, a qualitative analysis of video sequences was carried out. The presence of coralligenous concretions was mapped along the dive track (according to the time of occurrence on videos and the ROV's post-processed USBL data) and compared with geophysical data, to associate the presence of coralligenous with specific acoustic facies and/or morphological features and to extrapolate results over larger areas. Based on video observations, acoustic facies and seafloor morphologies, two main categories of coralligenous reefs were recognized and mapped: i) continuous coralligenous reefs and b) scattered coralligenous reefs (from sub-metric to metric dimensions) over sedimentary bottoms.

A quantitative analysis of ROV videos was then carried out to assess the environmental status of the coralligenous assemblages, using the MACS multi-parametric index (Enrichetti et al., 2019b). The MACS index integrates a set of parameters obtainable from Remotely Operated Vehicles (ROV) video footage that are derived from the Italian MSFD protocol (MATTM-ISPRA, 2019) for monitoring mesophotic coralligenous and rocky reefs. The protocol includes a standard sampling design conceived to gather various quantitative components, such as the occurrence and extent of the habitat (either biogenic or rocky reefs), the silt cover and the abundance, population structure and health status of habitat-forming megabenthic species, as well as abundance and typology of marine litter. To calculate the MACS index, three replicated 200 m-long transects were obtained from the ROV footage in each site (Fig. 2, Table 1). Location of these transects was defined to include sectors with most diffuse presence of coralligenous concretions and higher occurrence of structuring species forming the canopy. Within each transect, 20 random high-definition pictures targeting hard bottom were also extracted.

Following the methodology described in Enrichetti et al. (2019b), all the conspicuous megabenthic sessile and sedentary species of hard bottom in the intermediate and upper layers (*sensu* Gatti et al., 2015)

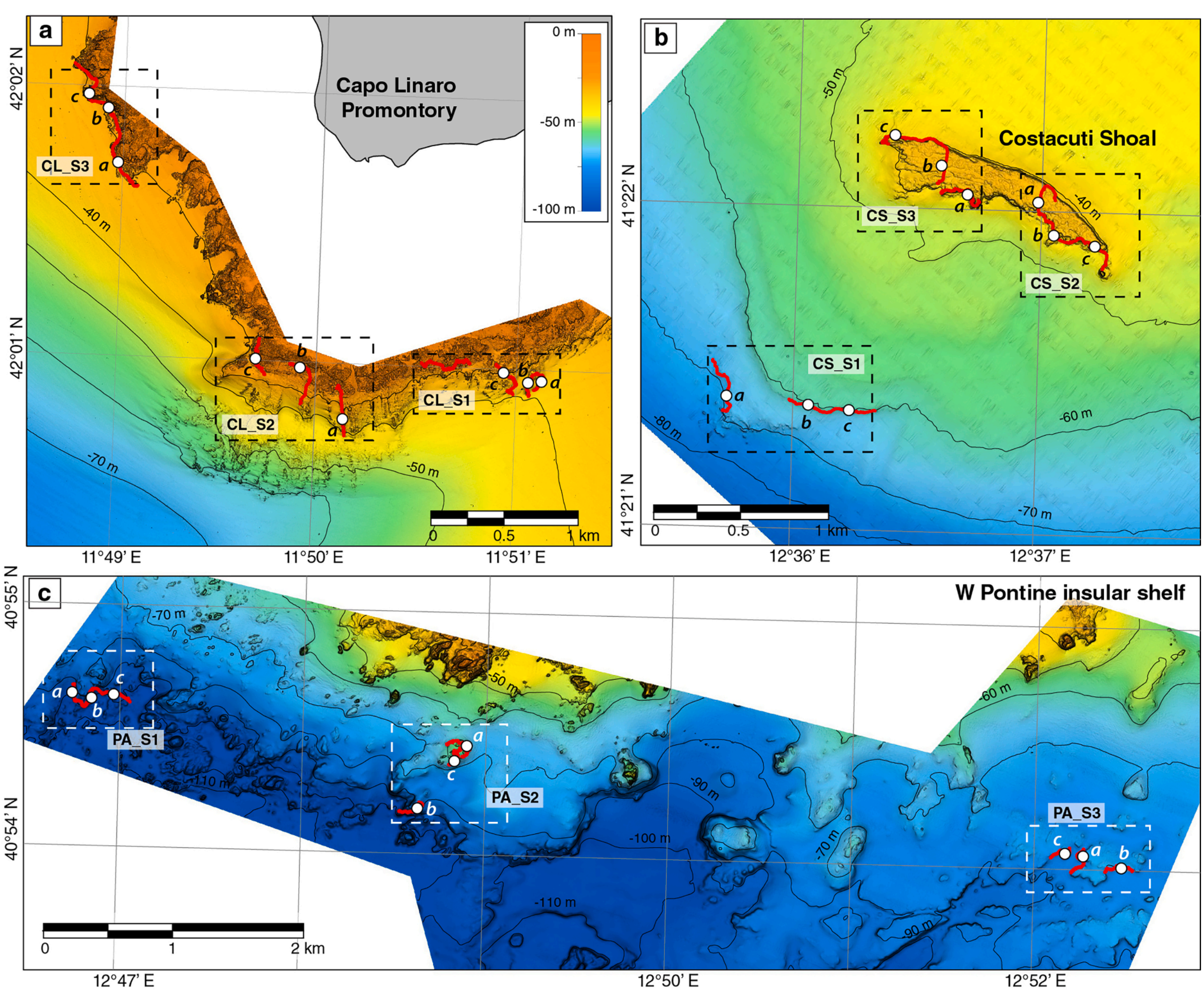


**Fig. 2.** Shaded relief maps of the study areas from MBES data, showing the ROV navigation tracks (red lines), the sites ID and the approximate location of the 200-m long transects extracted for the quantitative analyses and application of MACS index. Contour lines every 10 m.

**Table 1**
Summary of ROV dives performed in the three study areas. Length and depth range of the dive is shown, along with the ID of the 200-m long transects extracted from the ROV dives for the quantitative analyses and estimation of MACS index.

| Area | Site ID | Dive | Coordinates | | | | Length (m) | Depth Range (m) | 200-m transect |
|---|---|---|---|---|---|---|---|---|---|
| | | | Start | | End | | | | |
| Capo Linaro Promontory | CL_S1 | ROV_01 | 42°0.928′N | 11°51.086′E | 42°0.905′N | 11°51.059′E | 525 | 31–39 | CL_S1a-b |
| | | ROV_02 | 42°0.911′N | 11°50.982′E | 42°1.020′N | 11°50.894′E | 550 | 26–39 | CL_S1c |
| | | ROV_03 | 42°1.018′N | 11°50.759′E | 42°1.016′N | 11°50.522′E | 835 | 21–28 | (data used only for mapping purposes) |
| | CL_S2 | ROV_04 | 42°0.734′N | 11°50.148′E | 42°0.909′N | 11°50.104′E | 490 | 21–41 | CL_S2a |
| | | ROV_05 | 42°0.847′N | 11°49.925′E | 42°0.995′N | 11°49.866′E | 480 | 20–34 | CL_S2b |
| | | ROV_06 | 42°0.950′N | 11°49.743′E | 42°1.084′N | 11°49.711′E | 380 | 20–27 | CL_S2c |
| | CL_S3 | ROV_07 | 42°1.635′N | 11°49.077′E | 42°1.898′N | 11°48.932′E | 815 | 24–32 | CL_S3a |
| | | ROV_08 | 42°1.895′N | 11°48.943′E | 42°2.082′N | 11°48.743′E | 875 | 19–31 | CL_S3b-c |
| Costacuti Shoal | CS_S1 | ROV_09 | 41°21.515′N | 12°35.669′E | 41°21.359′N | 12°35.714′E | 460 | 67–70 | CS_S1a |
| | | ROV_10 | 41°21.399′N | 12°35.985′E | 41°21.371′N | 12°36.339′E | 585 | 60–62 | CS_S1b-c |
| | CS_S2 | ROV_11 | 41°22.035′N | 12°37.054′E | 41°21.828′N | 12°37.254′E | 1065 | 35–44 | CS_S2a-b-c |
| | CS_S3 | ROV_12 | 41°22.030′N | 12°36.738′E | 41°22.056′N | 12°36.594′E | 415 | 33–41 | CS_S3a |
| | | ROV_13 | 41°22.078′N | 12°36.568′E | 41°22.196′N | 12°36.365′E | 790 | 34–43 | CS_S3b-c |
| Palmarola Shelf | PA_S1 | ROV_14 | 40°54.663′N | 12°46.741′E | 40°54.596′N | 12°47.054′E | 855 | 89–105 | PA_S1a-b-c |
| | PA_S2 | ROV_15 | 40°54.404′N | 12°48.872′E | 40°54.454′N | 12°48.787′E | 380 | 55–62 | PA_S2a |
| | | ROV_16 | 40°54.171′N | 12°48.536′E | 40°54.211′N | 12°48.644′E | 280 | 73–95 | PA_S2b |
| | | ROV_17 | 40°54.370′N | 12°48.801′E | 40°54.439′N | 12°48.859′E | 350 | 53–64 | PA_S2c |
| | PA_S3 | ROV_18 | 40°54.084′N | 12°52.273′E | 40°53.986′N | 12°52.208′E | 320 | 72–76 | PA_S3a |
| | | ROV_19 | 40°53.992′N | 12°52.393′E | 40°53.997′N | 12°52.540′E | 280 | 71–75 | PA_S3b |
| | | ROV_20 | 40°54.046′N | 12°52.095′E | 40°54.086′N | 12°52.196′E | 290 | 73–77 | PA_S3c |

were identified and counted along the video transects. Organisms were identified to lowest general taxonomic levels possible from visual identification. Some taxa could only be identified to higher taxonomic categories due to difficulty in identification without the collection of specimens. The mean height of structuring species and their density (expressed as n° of colonies or individual/m$^2$ and referred to the extent of hard bottom surface occurring in each transect) were estimated. For all structuring anthozoan, the percentage of colonies with signs of epibiosis, necrosis and directly entangled in lost fishing gears were calculated. Marine litter was identified, classified into two categories of general litter (GL) and lost fishing gears (LFG), and its density (expressed as n° of items/m$^2$) was computed for each transect.

The analysis of photos included the determination for each photo of four parameters, each one classified into four categories following an ordinal scale. Specifically, the slope of substratum was estimated according to the classes: 0°, <30°, 30°–80°, >80°. The sedimentation level and the basal living cover (i.e., the percentage of hard bottom covered by organisms of the basal and intermediate layers smaller than 10 cm in height) were estimated and classified according to the categories: 0%, < 30%, 30–60%, > 60%. Finally, considering the percentage of basal living cover represented by encrusting coralline algae, the coralline algae cover was determined as: absent, sparse, abundant, very abundant. Modal classes for each transect were calculated.

### 2.2.2. MACS index determination

From the analysis of videos and photos twelve indicators for the determination of MACS index were obtained for each 200-m long ROV transect:

i) Species richness (SR)
ii) Basal biocover (BC)
iii) Coralline algae cover (CC)
iv) Dominance of structuring species (DM)
v) Density of all structuring species (SSD)
vi) Mean height of dominant structuring species (SSH)
vii) Sedimentation (SD)
viii) Percentage of entangled colonies (ENT)
ix) Percentage of necrotic colonies (NCR)
x) Percentage of epibionted colonies (EPB)
xi) Density of litter items (LD)
xii) Litter typology (LT)

The MACS index is composed of two independent units, the Index of Status ($I_s$) and the Index of Impact ($I_i$). $I_s$ depicts the status of the benthic communities by focusing on conspicuous species diversity, basal layer status and canopy condition, which correspond to the first six metrics (SR, BC, CC, DM, SSD, SSH); $I_i$ defines the impacts affecting the investigated ecosystems by considering the sedimentation level, the percentage of damaged structuring anthozoans and the occurrence of marine litter (SD, ENT, NCR, EPB, LD, LT).

A score from 0 to 3 was assigned to each metric, following the ordinal ranks reported in Enrichetti et al. (2019b). The Ecological Quality Ratio (EQR) for each metric was then computed, by dividing for three (the maximum value expected) and multiplying for 100 (the scale of EQR). Reference conditions for coralline algae cover and sedimentation were defined considering the depth of the observations and the slope together with distance from river mouths, respectively. For details see Enrichetti et al. (2019b).

The two indices ($I_s$ and $I_i$) were aggregated for each transect by averaging the EQR of the corresponding metrics. The mean values of $I_s$ and $I_i$ for each site were then computed by averaging the values of the three replicated transects. Final MACS index was obtained by combining the index of status and of impact using the formula:

$$MACS = \frac{Is + (100 - Ii)}{2}$$

The indices for all sites were finally classified using the classes of environmental quality status defined in Enrichetti et al. (2019b).

## 3. Results

### 3.1. Geomorphology and coralligenous habitat distribution

The analysis of multibeam and side scan sonar data in the study areas revealed a variety of morphological features and acoustic facies associated with coralligenous reefs (Figs. 3 and 4). ROV videos confirmed the occurrence of coralligenous in all the explored sites, with different morphotypes ranging from large and continuous reefs along cliffs, banks and large blocks to small (sub-metric to metric dimensions) scattered concretions over sedimentary bottoms. The extent and distribution of

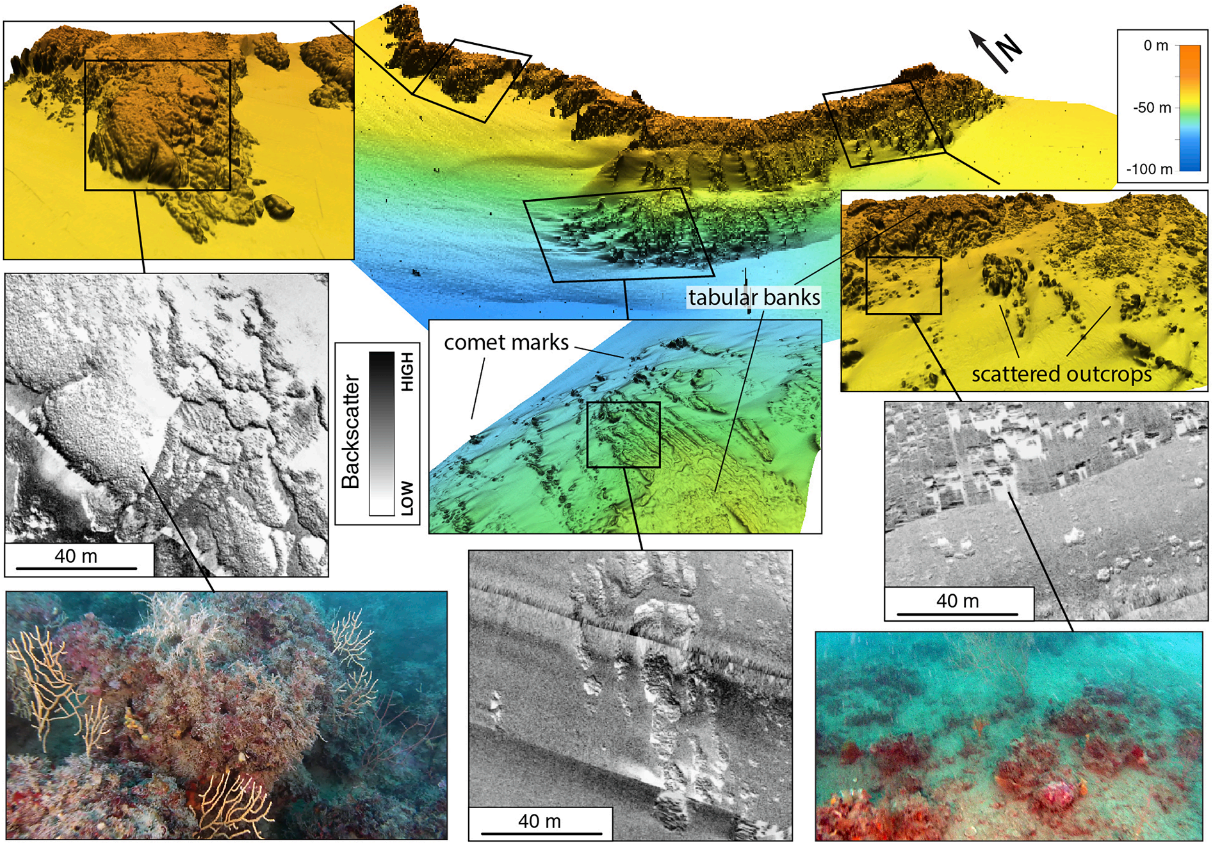


**Fig. 3.** 3D perspective view of the Capo Linaro area, showing the main morphological features and acoustic facies associated with the presence of coralligenous reefs.

coralligenous across the study areas (Fig. 5) is highly variable, in relation to the different geomorphological setting and the occurrence of hard substrates.

### 3.1.1. *Capo linaro promontory*

The area offshore Capo Linaro Promontory, comprised between 10 and 75 m depth, shows a complex morphology in relation to the submerged prosecution of the promontory, which forms an almost continuous belt of rocky outcrops down to 30 m depth (Fig. 3). Therefore, a widespread occurrence of coralligenous concretions is observed in the coastal sectors of this area (Fig. 5a). Continuous coralligenous reefs develop over large reliefs (hundreds of meters wide and 10–15 m high) with local slopes up to 50°, in the northern sector, as well as on tabular banks 3 to 5 m high, with irregular shapes and rugged surface, occurring in the central and eastern sectors. These features are characterized by a heterogeneous distribution of backscatter intensity, with spackled pattern of intermediate to high backscatter values associated with null backscatter (shadow effect) (Fig. 3). Coralligenous reefs are also observed on sparse reliefs encompassing large blocks (tens of meters wide and 1 to 10 m high), and small outcrops of metric and sub-metric dimensions, scattered on the sedimentary bottoms between 30 and 60 m depth (Figs. 3 and 5a). In the central sector (and to a lesser extent in the eastern sector), comet marks have formed in association with these reliefs and suggest the action of bottom currents flowing northwestward parallel to the coastline (Fig. 3). A spackled pattern of intermediate to very high backscatter values with shadow zones also characterizes the sparse outcrops, strongly different from the homogeneous distribution of medium backscatter values over the adjacent sedimentary seafloor (Fig. 3).

### 3.1.2. *Costacuti Shoal*

The seafloor of the Costacuti area, between 40 and 85 m depth, is overall characterized by a smooth morphology except for the presence of the Costacuti Shoal, an isolated outcrop about 1500 m long, 150–350 m wide and 8–10 m high, and for sparse reliefs, few meter to few hundreds of meters wide and 1–2 m high, located about 1.5 km offshore the shoal (Fig. 4a). Coralligenous concretions only occur in correspondence of these features (Fig. 5b). Specifically, large coralligenous reefs are observed along the flanks of the Costacuti Shoal. These are about 6–8 m high with mean gradients of 15-20°, locally reaching 40°, and are characterized by a similar acoustic facies of the Capo Linaro outcrops, with heterogeneous pattern of medium to high backscatter and shadow zones (Fig. 4a). The southwestern flank is overall characterized by a much irregular morphology than the rectilinear scarps bordering the northeastern side of the shoal (Fig. 4a). The sub-horizontal summit of the shoal, located at 35 m depth, displays a rugged morphology produced by small reliefs about 0.2–1 m high (Fig. 4a). Coralligenous concretions are observed in correspondence of these reliefs, surrounded by sandy seafloor. The side scan sonar mosaic shows the presence of bedforms on the sandy seafloor, while the small reliefs are characterized by a heterogeneous distribution of low to medium backscatter (Fig. 4a).

Sparse coralligenous reefs also develop on the reliefs offshore the shoal (Fig. 5b), characterized by spackled pattern of intermediate to high backscatter values, surrounded by a prevalent muddy seafloor, which in turn is associated with a homogeneous low backscatter facies (Fig. 4a).

### 3.1.3. *Palmarola insular shelf*

Palmarola insular shelf is characterized by a marked morphological complexity due to the widespread occurrence of reliefs of variable dimension and shape evenly distributed across the study area between 50 and 110 m depth (Fig. 4b). A mosaic of coralligenous habitats including large and continuous reefs and small concretions of metric and sub-metric dimensions was observed in correspondence of the reliefs

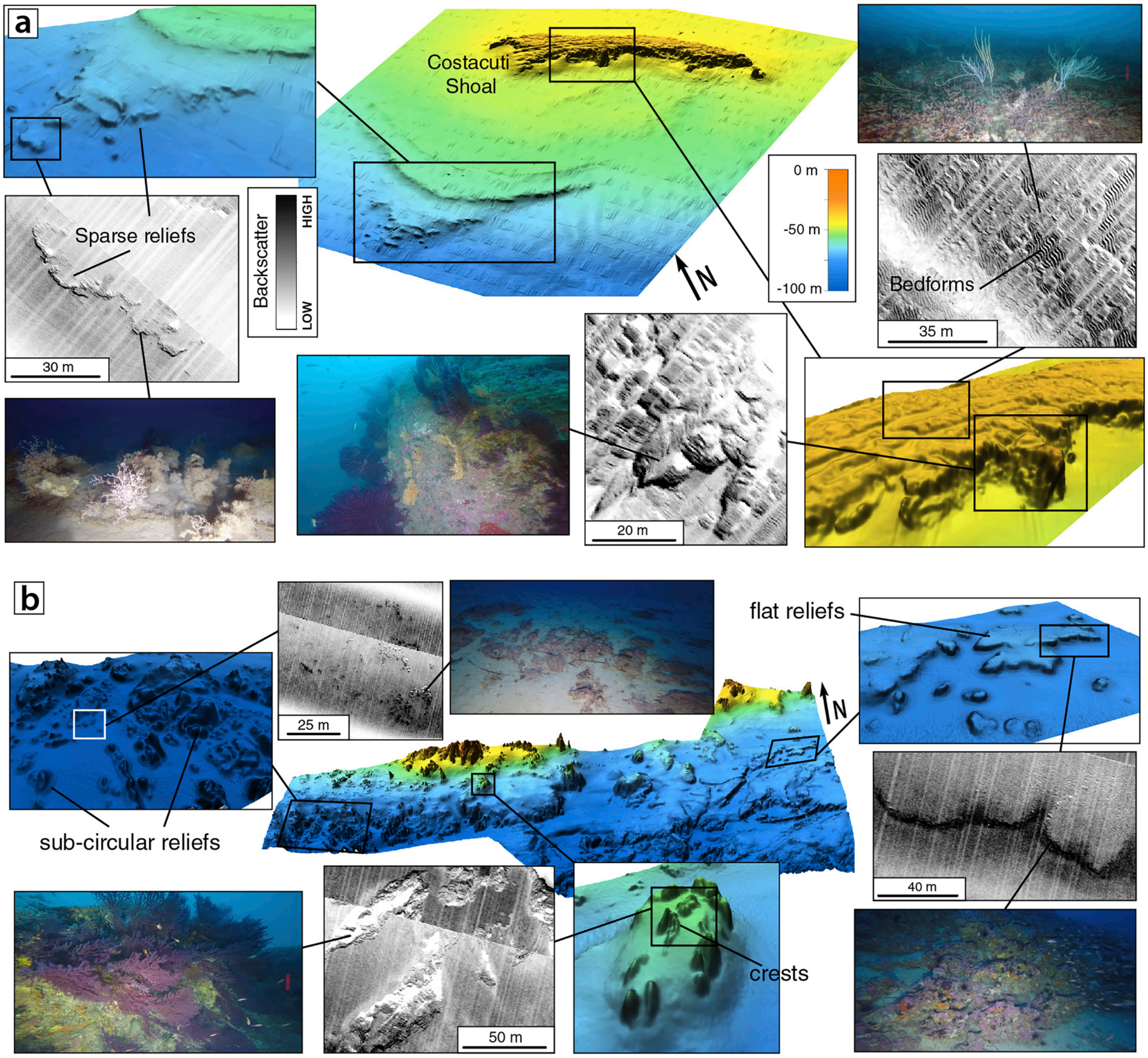


**Fig. 4.** 3D perspective views of the (a) Costacuti Shoal and (b) Palmarola insular shelf, showing the main morphological features and acoustic facies associated to the presence of coralligenous reefs.

(Fig. 5c), interspersed on rhodolith beds and bioclastic sands. Specifically, coralligenous reefs are present along the summit crests and the steep scarps (15-20°, up to 50°) of sub-circular reliefs tens to hundreds of meters wide, associated with a spackled pattern of intermediate to high backscatter values (Fig. 4b), as well as along the scarps of flat reliefs hundreds of meters wide, associated to an homogeneous high backscatter facies (Fig. 4b). Scattered coralligenous concretions are also widespread on flat areas among the reliefs (Fig. 5c), in correspondence of small patches of high backscatter values that can be observed on the side scan sonar mosaic (Fig. 4b).

### 3.2. Coralligenous assemblages and anthropic impacts

The quantitative analysis of the ROV video images allowed recognizing the presence of 79 taxa belonging to 10 phyla (Chlorophyta, Rhodophyta, Porifera, Cnidaria, Echinodermata, Bryozoa, Annelida, Mollusca, Arthropoda and Chordata) across all studied stations (SM1). The higher number of taxa was observed in the Costacuti area (n = 55), followed by Palmarola insular shelf (n = 52) and Capo Linaro Promotory (n = 40), while only 22 taxa were shared by all the study areas (SM1).

Conspicuous megabenthic species richness showed a marked variability across transects (SM2); for instance, the highest and lowest species richness, of 22 and 9 species respectively, were found in two transects of the same site at Costacuti Shoal (CS_S3, SM2). Species richness ranged from 16 to 22 species at Capo Linaro and from 10 to 19 species at Palmarola insular shelf (SM2).

A total of 13 structuring species (with over 6644 individuals or colonies counted) was recorded in the video-transects (Fig. 6): four sponges (*Axinella cannabina*, *A. polypoides*, *Spongia lamella*, *Sarcotragus foetidus*), one scleractinian (*Cladocora caespitosa*), one antipatharian (*Antipathella subpinnata*), five octocorals (*Corallium rubrum*, *Paramuricea clavata*, *Eunicella cavolini*, *E. singularis*, *Leptogorgia sarmentosa*), and two bryozoans (*Myriapora truncata*, *Pentapora fascialis*). These were distributed with variable abundance across the study areas, ranging from 0.01 to 4.1 col/m$^2$ (Fig. 7 and SM2).

Overall, the highest densities of structuring species (SSD, from 1 to 4 col/m$^2$) were recorded at Capo Linaro Promontory where monospecific forests dominated by *C. rubrum* were observed, along with oligospecific and polyspecific assemblages featuring *P. clavata*, *A. cannabina* and *L. sarmentosa* as the most commonly recorded species together with *C. rubrum* (Fig. 7).

Costacuti Shoal was characterized by a high heterogeneity in the distribution of structuring species (Fig. 7), alternating transects with SSD between 1.1 and 2.3 col/m$^2$, forming monospecific and

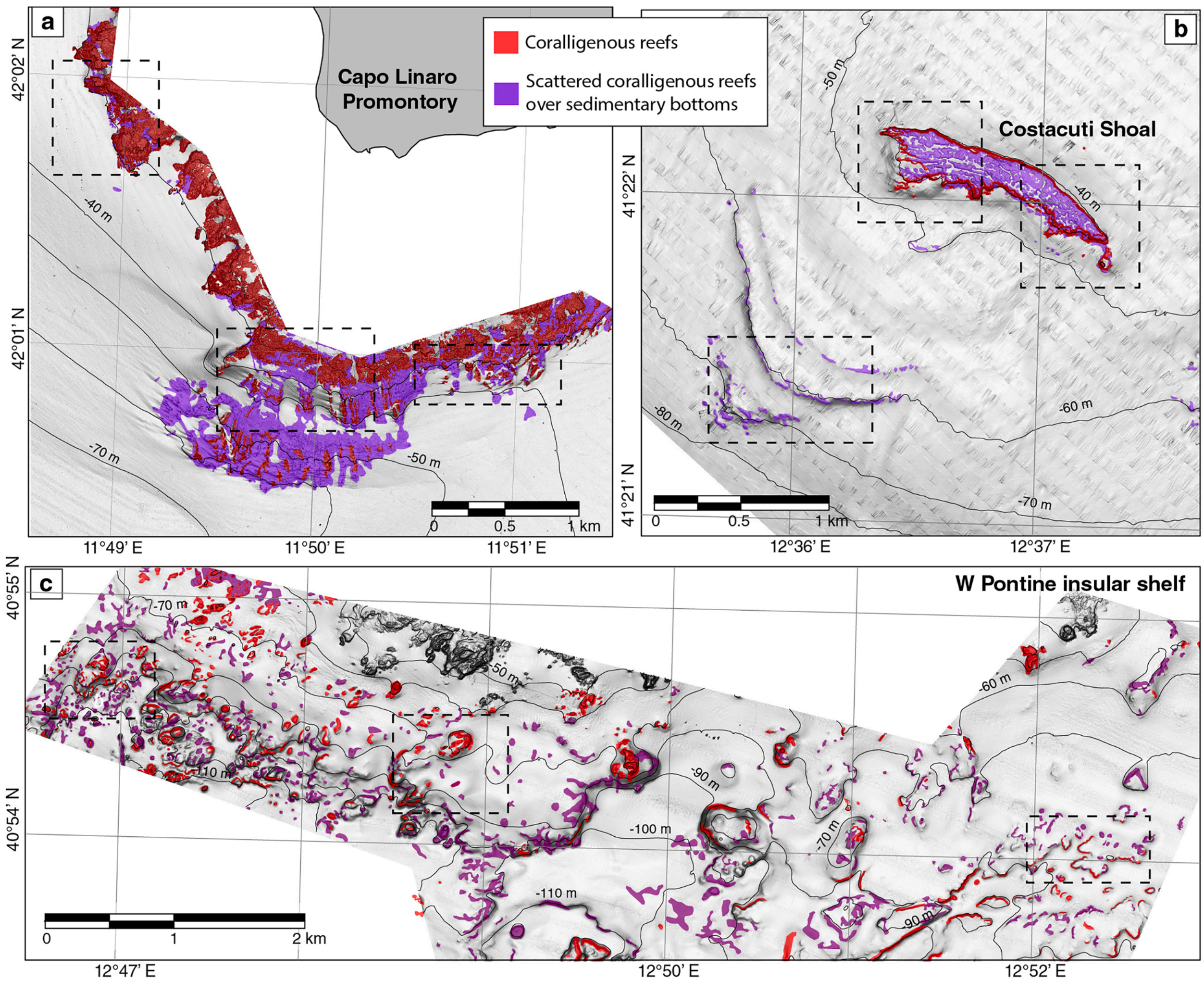


**Fig. 5.** Distribution maps of coralligenous habitats in the (a) Capo Linaro, (b) Costacuti and (c) Palmarola study areas. The dashed black rectangles denote the sites where groundtruthing ROV surveys were carried out. Contour lines every 10 m.

oligospecific forests mostly dominated by the three species of gorgonians *P. clavata*, *E. cavolini* and *E. singularis*, and transects characterized by a paucity of structuring species, with densities < 0.5 col/m$^2$ (Fig. 7).

An extreme paucity of structuring species was also observed in the Palmarola area, where the majority of transects showed SSD < 0.5 col/m$^2$ (Fig. 7). The only exception is represented by the two shallower transects (about 60 m depth) performed in this area, where oligospecific forests dominated by *P. clavata* and *E. cavolini* were observed (Fig. 7 and SM2).

The basal living cover reached the highest values in the sites of Palmarola insular shelf and the lowest offshore Costacuti Shoal (CS_S1, SM2). Similarly, coralline algae cover was higher at Palmarola insular shelf, where abundant living coralline algae were observed down to 105 m depth, and very low to completely absent offshore Costacuti Shoal and in the eastern site of Capo Linaro Promontory (CS_S1 and CL_S1, SM2).

Sedimentation levels were generally high in the sites of Capo Linaro and offshore Costacuti Shoal, while lower sedimentation was observed in correspondence of the Costacuti Shoal and at Palmarola insular shelf (SM2).

As regards the observed anthropic impacts, marine litter was recorded in all study areas, with variable densities ranging from 0.005 to 0.19 items/m$^2$ (Fig. 8). Only two transects on the Palmarola insular shelf were completely litter-free. Recorded items included lost fishing gears (mainly related to small-scale artisanal fishery, such as longlines, ropes and subordinately nets) and general litter (including plastic bags and bottles, tires, glass and metal objects) (Fig. 9). Fishing-related litter was present in 92% of the investigated sites and 52% also showed general litter, despite the abundance of this last type of anthropic debris was much lower than that of artisanal lost fishing gear. The highest litter density was observed at Costacuti Shoal, while Palmarola insular shelf was overall characterized by a very low occurrence of litter (Fig. 8 and SM2).

Entanglement of structuring anthozoan by demersal fishing gears was rarely observed (SM2), involving the 0.34% and 5.7% of total anthozoan colonies in the Capo Linaro and Costacuti areas, respectively, while this impact was not recorded in the Palmarola area. Conversely, necrotic and epibiont-covered colonies were observed in all three areas, with higher percentages observed at Costacuti Shoal, followed by Capo Linaro and Palmarola sites (SM2).

Furthermore, evidences of bottom trawling activities were observed at Capo Linaro and Costacuti areas, where the side scan sonar mosaics showed the widespread occurrence of trawl marks over the sedimentary soft bottoms surrounding the coralligenous outcrops (Fig. 9g,h).

### 3.3. MACS index outcomes

MACS index in the three study areas ranged from 44 to 70, with $I_s$ comprised between 35 and 57 and $I_i$ between 17 and 50 (SM3). The highest value for the status of the benthic community was obtained in the shallower site of Palmarola insular shelf, whereas the lowest value

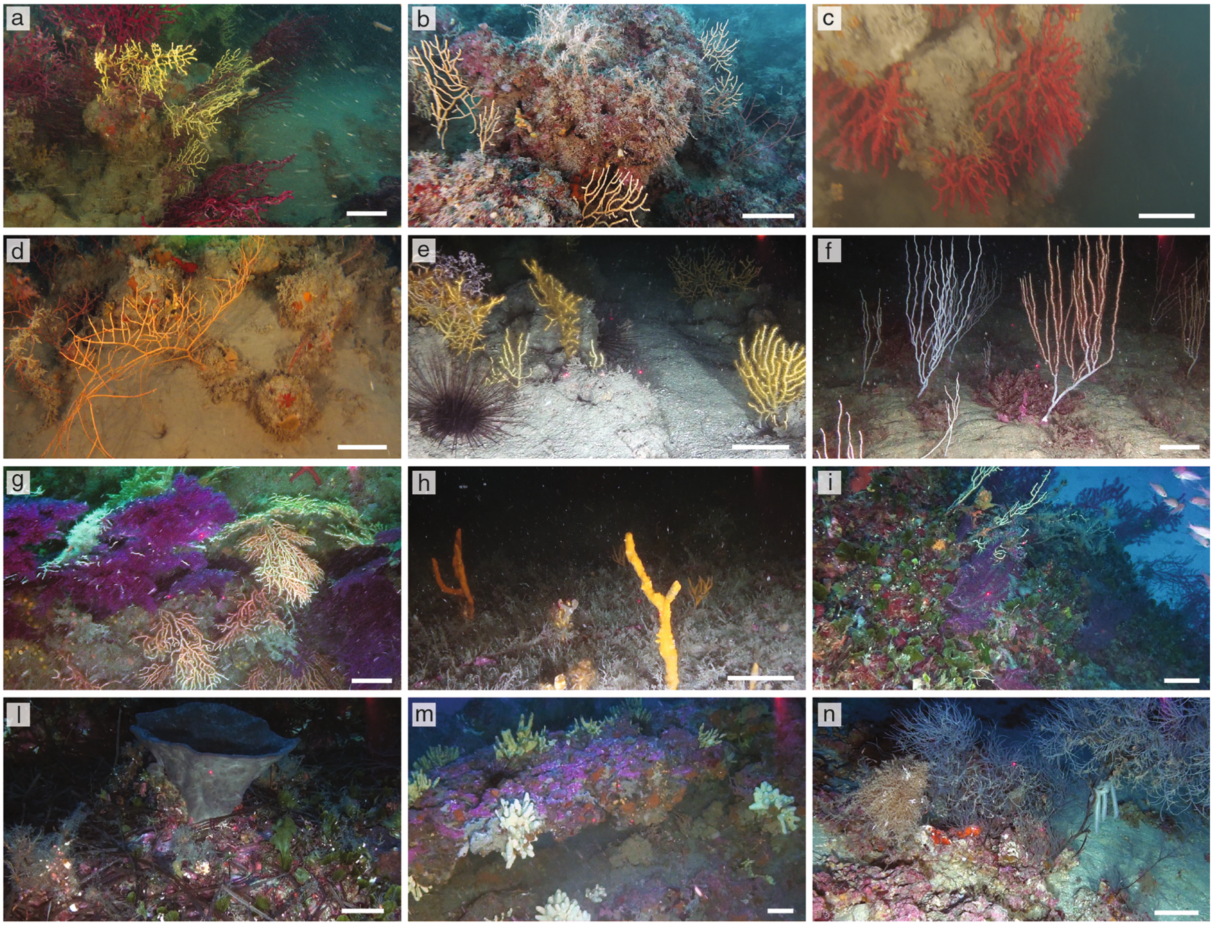


**Fig. 6.** ROV images showing some of the species observed in the (a-d) Capo Linaro, (e-h) Costacuti and (i-n) Palmarola study areas. a) *Paramuricea clavata*, 36 m depth; b) *Eunicella cavolini*, 20 m depth; c) *Corallium rubrum*, 38 m depth; d) *Leptogorgia sarmentosa*, 35 m depth; e) *E. cavolini*, 61 m depth; f) *E. singularis*, 35 m depth; g) *E. cavolini* and *P. clavata* 34 m depth; h) *Axinella cannabina*, 43 m depth; i) *E. cavolini* and *P. clavata* 59 m depth; l) *Spongia lamella* 56 m depth; m) *Aplysina cavernicola*, 74 m depth; n) *Antipathella subpinnata*, 72 m depth. Scale bar = approx. 10 cm.

was reported from the site offshore Costacuti Shoal (Fig. 10a-c). The highest impact was recorded at Costacuti Shoal, while the less disturbed sites were observed at the Palmarola insular shelf (Fig. 10d-f).

Overall, MACS application to the sites of the Latium continental margin highlighted different situations ranging from poor to high environmental status, with several combinations of $I_s$ and $I_i$ (Fig. 10 and SM3) reflecting the high variability of environmental settings and human pressures.

The highest environmental status was found at the shallower site of Palmarola insular shelf, where a good $I_s$ combined with a very low $I_i$ (PA_S2, Fig. 10). Conversely, a poor environmental status was observed offshore Costacuti Shoal, because of a bad $I_s$ and moderate $I_i$ (CS_S1, Fig. 10). The sites characterized by a good environmental status at Costacuti and Capo Linaro areas, showed a combination of moderate $I_s$ and low $I_i$ (CS_S3 and CL_S2, Fig. 10). The sites characterized by a moderate environmental status might show different situations: poor $I_s$ and a very low $I_i$ characterized the deeper sites at Palmarola insular shelf (PA_S1 and PA_S3, Fig. 10), while a combination of moderate $I_s$ and moderate-low $I_i$ was observed at Costacuti and Capo Linaro areas (CL_S1, CL_S3, and CS_S2, Fig. 10)

## 4. Discussion

### *4.1. Mapping coralligenous distribution*

In this study, the distribution of coralligenous reefs in three sectors of the Latium continental shelf was mapped using a methodological approach that involves a combination of full-coverage information from acoustic instruments and fine-scale observations conducted over smaller extents through video surveys (Brown et al., 2011). The usefulness of seabed mapping techniques for environmental monitoring, based on the recognition that seafloor physical characteristics, such as substratum type, sediment composition and geomorphology are important descriptors of biological patterns and can be used as proxies to predict their distribution, has been well established (e.g., Kostylev et al., 2001; Beaman & Harris, 2007; Buhl-Mortensen et al., 2015; Pierdomenico et al., 2015; Pierdomenico et al., 2017). Using acoustic remote sensing techniques, coupled with *in situ* sampling, to map the distribution of valuable ecosystems such as coralligenous, provides information on a scale relevant for conservation purposes and large scale management in a more practical way compared with standard biological observations, which requires much larger efforts to cover large areas (Zapata-Ramírez et al., 2013).

On the other hand, along with the assessment of coralligenous environmental status, the Italian MSFD protocol for monitoring mesophotic coralligenous and rocky reefs (MATTM-ISPRA, 2019) specifically requires the definition of the extent and spatial distribution of coralligenous reefs using MBES and SSS data. In fact, despite the high ecological and biodiversity importance attributed to these bioconstructions (Ballesteros, 2006), a major barrier to meet conservation and management requirements is that their distribution remains poorly characterized. Although we have an overall knowledge about the composition of the Mediterranean coralligenous assemblages (Casas-Güell et al., 2015; Çinar et al., 2020), the paucity of high-resolution

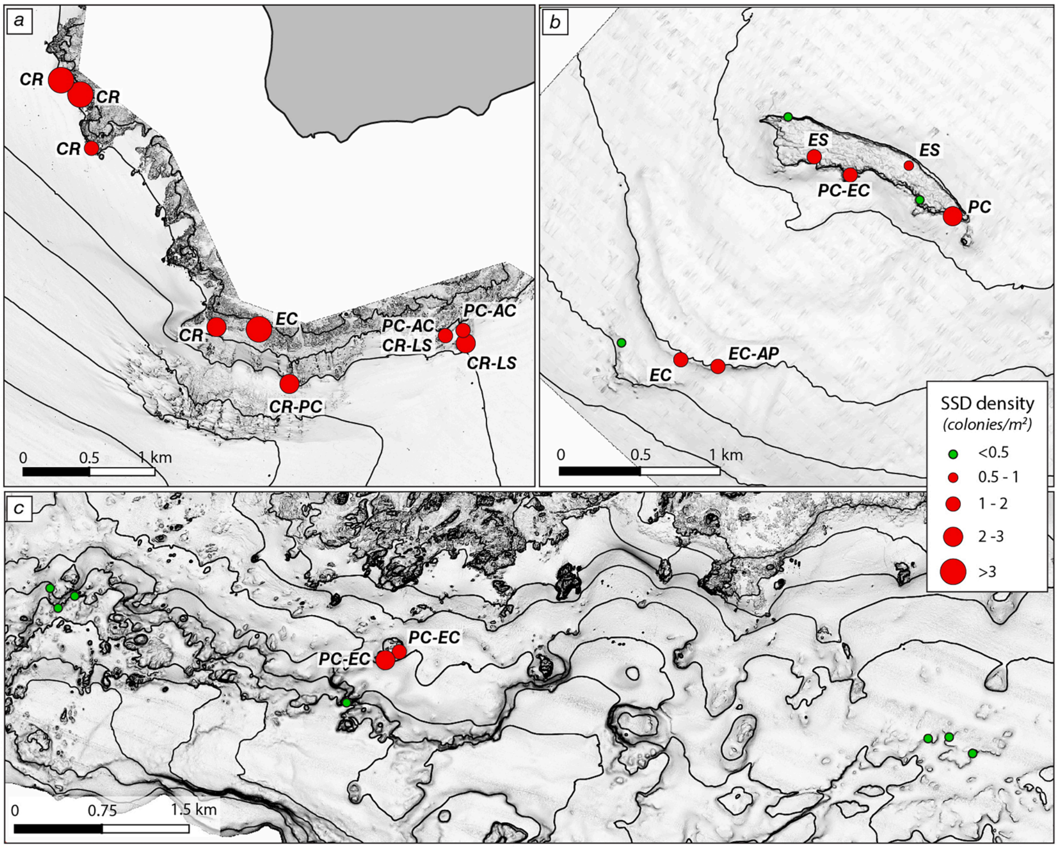


**Fig. 7.** Density of all structuring species and dominant species across transects in the (a) Capo Linaro, (b) Costacuti and (c) Palmarola study areas. Dominant species were evaluated considering the number of structuring species reaching an abundance higher than the mean value per transect of the entire structuring assemblage. PC- *Paramuricea clavata*; EC – *Eunicella cavolini*; ES – *Eunicella singularis*; LS – *Leptogorgia sarmentosa*; CR – *Corallium rubrum*; AP – *Axinella polypoides*; AC – *Axinella cannabina.*

cartographic information is considered one of the greatest lacunae from the conservation point of view (Agnesi et al., 2009; Pergent, 2011). Predictive large-scale models estimate that as much as 95% of coralligenous reefs may still need to be mapped across the Mediterranean Sea (Martin et al., 2014), especially in the eastern and southern part of the basin. At local scale, some progress in cartographical data have been acquired, especially in marine protected areas (Zapata-Ramírez et al., 2016; UNEP-MAP-RAC/SPA, 2008), although, we lack of an overall precise distribution information on coralligenous and other calcareous bioconstructions, due to their intrinsic heterogeneous distribution and the technical and financial constraints of field mapping operations resulting in an unbalanced mapping efforts (UNEP-MAP-RAC/SPA, 2008; 2017).

Compared to other country bordering the Mediterranean Sea, sampling intensity along the Italian coasts has been relatively high (Martin et al., 2014), despite being very uneven across the different regions. Large mapping efforts addressing coralligenous reefs have been made in the Southern Adriatic and Ionian Sea within regional projects (Campiani et al., 2014; Marchese et al., 2020), as well as in the Ligurian Sea (Cánovas Molina et al., 2011). For the Latium region, fine-scale distribution maps of coastal habitats (<100 m depth), including coralligenous, have been provided by Ardizzone et al. (2018). However, a significant lack of knowledge still exists about the coralligenous assemblage structure, for which few and sparse information are available (i.e. Casoli et al., 2020; Piazzi et al., 2017; Piazzi et al., 2021).

As regards the geoacoustic signatures indicative of coralligenous presence, along the Latium shelf coralligenous reefs were typically related to acoustic facies with intermediate to high backscatter (Figs. 3 and 4), with different textures in relation to the variety of shapes and the lateral continuity that these bioconcretions displayed in the explored locations, similarly to what observed by Bracchi et al. (2015) in the Adriatic Sea and by Ingrassia et al. (2019) and Sañé et al. (2021) on the western Pontine insular shelf. Coralligenous seascapes were either found as continuous reefs developing over rocky cliffs and banks and as concretions covering blocks of various dimension (from hundreds to few meters), to sub-metric scattered outcrops over sedimentary bottoms. This confirms the high complexity of coralline algae formations and their morphological expressions related to the variability of geomorphological settings prone for the development of these bioconcretions (Cánovas Molina et al., 2011), which in turn reflects on the structure and characteristics of the associated fauna, as discussed in the next paragraph.

### *4.2. Influence of environmental and anthropic factors on the characteristics and environmental status of coralligenous along the Latium margin*

Coralligenous ecosystems can be defined as highly heterogeneous systems, where the environmental variables together with distribution and abundances of taxa can differ greatly on both a regional and a local scale (Casas-Güell et al., 2015; Çinar et al., 2020). The coralligenous reefs in the Latium region show high spatial, morphological and biological variability (Figs. 5 and 6), that seems to be mostly controlled by differences in geological-oceanographic conditions along the continental margin.

The geological setting of the area has an obvious prominent role in determining the availability and the morphology of hard substrates necessary to the development of coralligenous reefs (Ballesteros, 2006)

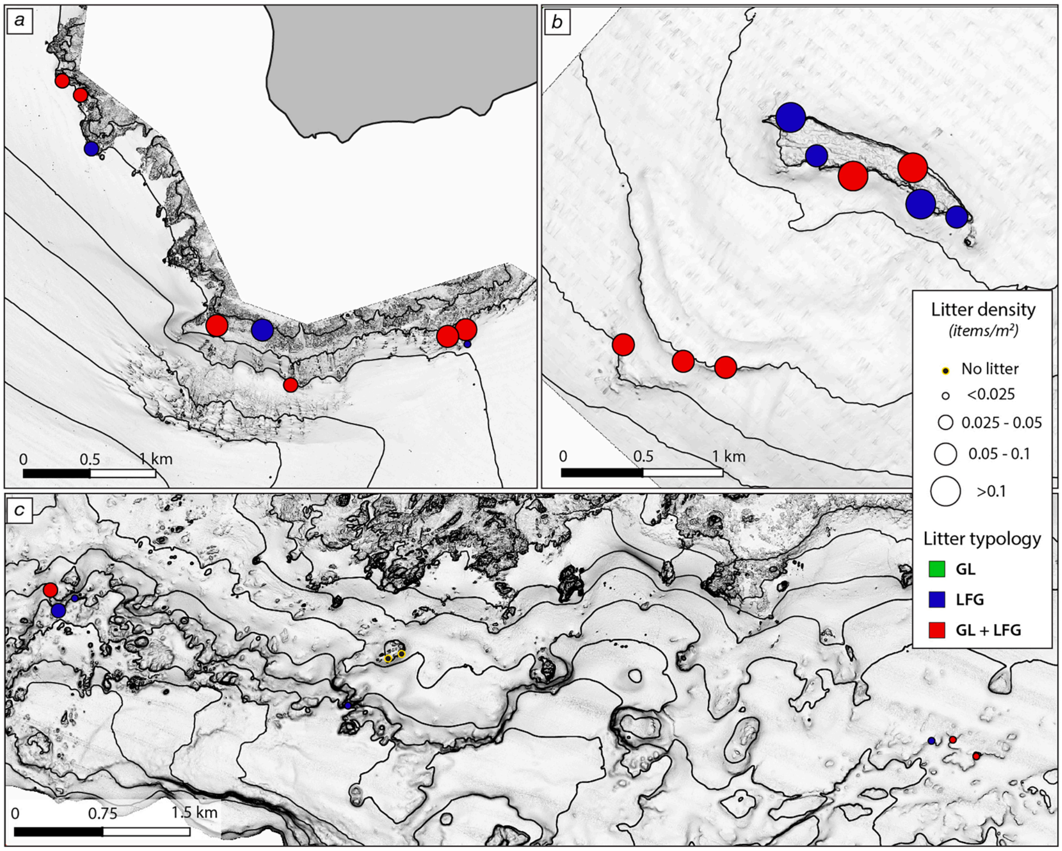


**Fig. 8.** Density and typology of marine litter recorded across transects in the (a) Capo Linaro, (b) Costacuti and (c) Palmarola study areas.

and explains the large differences in the distribution of coralligenous between Capo Linaro and Costacuti area, where coralligenous reefs develop over pre-existent outcropping or suboutcropping rocks (Laborel, 1987). Conversely, along Palmarola insular shelf, together with continuous reefs over morphostructural rocky and/or volcanic reliefs (Martorelli et al., 2012), we observed a widespread occurrence of small coralligenous concretions on flat bottoms interspersed on rhodolith beds. This led us to support the hypothesis that coralligenous in this area can also develop from the coalescence of free thalli or rhodoliths that are not located on a hard substrate (Pérès & Picard, 1952; Bracchi et al., 2015; Ingrassia et al., 2019).

The shallowest distribution of coralligenous was found in Capo Linaro, where living coralline algae were observed between 20 m and 60 depth. This may be related to higher sedimentary inputs and increased water turbidity, favoured by the proximity to the coast and the influence of Tiber River and other smaller rivers (Chiocci & La Monica, 1996: Pitarch et al., 2019). The interplay between enhanced sedimentation and intense hydrodynamics, due to the interaction of the submerged promontory with bottom currents, may contribute to the variability in biocoverage and coralline algae cover observed across transects (SM2).

At Costacuti Shoal, about 10 km from the coast, the low-moderate sedimentation and abundant living coralline algae in correspondence of the shoal contrasted with high sedimentation and almost complete absence of coralline algae in the deeper outcrops at 60–70 m depth, that may be related to the deposition of muddy sediments at higher depths reducing or hampering coralline growth (Piazzi et al., 2019). However, anthropic factors, specifically resuspension caused by bottom trawling, may contribute to the high sedimentation levels (Linders et al., 2018) in the deeper outcrops, as also suggested by the occurrence of trawl marks observed on the side scan sonar mosaics over sedimentary bottoms surrounding coralligenous reefs in the Costacuti as well as in the Capo Linaro area (Fig. 9g,h). Along Palmarola insular shelf, the low turbidity of waters, related to the low siliciclastic sediment input due the lack of a significant river runoff on the islands and their distance from the mainland, allows for a deeper penetration of the light, favouring development of thriving coralline algae down to > 100 m depth.

The high variability in composition and abundance of structuring species across areas and transects (Fig. 7), could be related to a combination of environmental parameters including depth, substratum complexity and food availability. Depth, whose gradients correlate with changes in other abiotic parameters such as light, temperature, oxygen, organic matter and pressure, is recognized as an important factor driving the structure of benthic communities (Garrabou et al., 2002). The wide depth range of the explored sites (20–40 m, 30–70 m and 50–100 m depth for Capo Linaro, Costacuti and Palmarola areas, respectively, Table 1) may thus influence the diversity of coralligenous assemblages observed in the different study areas. Furthermore, topographic heterogeneity over small spatial scales and associated changes in slope and substrate orientation, have a pivotal role in coralligenous assemblage structure, influencing sediment deposition, hydrodynamism and shading, therefore leading to the formation of several microhabitats (Ferdeghini et al., 2000; Balata et al., 2005; Virgilio et al., 2006). In the investigated areas, intense hydrodynamics may provide food supply to sustain well diversified assemblages dominated by benthic suspension feeders, featuring common anthozoan and sponge species of western Mediterranean coralligenous assemblages (SM1) (Valisano et al., 2019; Çinar et al., 2020). The action of bottom currents is witnessed by the occurrence of comet marks in the Capo Linaro area (Fig. 3) and bedforms fields on the summit and surrounding sectors of the Costacuti Shoal (Fig. 4), as well as by the presence of rodoliths beds, whose development is strongly associated with bottom currents (Pérès & Picard, 1964), over the insular shelf of Palmarola. It is known that the presence of suspension feeders in coralligenous ecosystems largely depends on current strength and availability of food (Ballesteros, 2006; Longo et al., 2018).

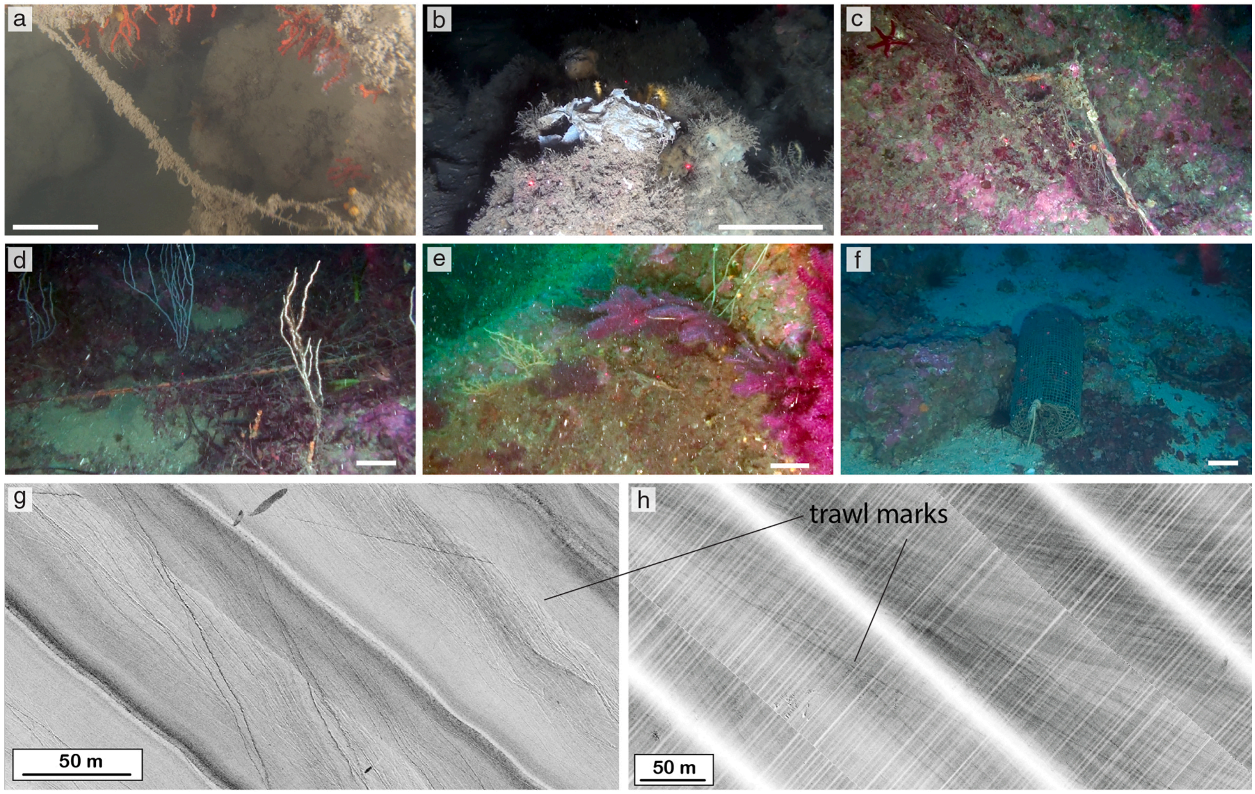


**Fig. 9.** Anthropic impacts in the studied areas. (a-f) ROV images showing some examples of marine litter observed in the study areas, mainly related to small-scale artisanal fishery activities. (a) fishing line; (b) plastic bag fragment; (c-d) fishing nets; (e) fishing line causing entanglement on *P. clavata* colonies; (f) pot. Scale bar approximately 10 cm. (g-h) Side scan sonar mosaics showing traces of trawl marks over sedimentary soft bottoms adjacent to coralligenous outcrops in the (g) Capo Linaro and (h) Costacuti areas.

In this sense, variability in the hydrodynamism may explain the strong zonation of structuring species observed across the different sectors of the Costacuti Shoal (Fig. 7). In fact, the southwestern flank of the shoal hosted dense populations of the gorgonians *P. clavata* and *E. cavolini*, the top was mostly dominated by *E. singularis*, while the northeastern flank was mostly characterized by the bryozoan *M. truncata* and the sponge *A. cavernicola* and by the almost total absence of gorgonians. Beside anthozoans, especially gorgonians, are able to form dense aggregations, which may contribute to patchiness in distribution (Gili et al., 1989; Bramanti et al., 2017; Rossi et al., 2017), the observed pattern could be linked to the action of the unidirectional northward flowing currents of Tyrrhenian surface waters (Pinardi & Masetti, 2000). This current is more intense on the exposed southwestern flank of the shoal compared to the northeastern one and especially focused on bulge-like structures, where the higher abundances of gorgonians were observed (Fig. 7). Gorgonians are generally reported to be abundant in areas rich in suspended organic matter, while sponges, bryozoans and scleractinian corals prefer more oligotrophic waters (Gili & Ballesteros, 1991; Çinar et al., 2020).

Overall, the anthropic impact on the studied areas, especially the damages on structuring species caused by fishing related debris, was not as severe as reported from other coralligenous and rocky outcrops across the western Mediterranean Sea (i.e., Consoli et al., 2019; Enrichetti et al., 2019a; Giusti et al., 2019). The predominance of lost fishing gears, particularly those related to artisanal fisheries such as lines, ropes and trammel nets, over general litter on biogenic structures is consistent with previous observation (Angiolillo, 2018). These gears can impact megabenthic communities causing mechanical damages and entanglement and the increase of the number of entangled, epibionted and necrotic colonies of structuring species with increasing number of lost gears, confirms the destructive effects of artisanal fishing activities (Bo et al., 2014; Consoli et al., 2019; Enrichetti et al., 2019a). In the Capo Linaro and Costacuti areas, a further disturbance may be envisaged in the resuspension of fine sediment caused by bottom trawling activities carried out over the sedimentary bottoms, although the resulting impact is not easy to distinguish from the effect of increased sedimentation due to natural processes. The very low impact recorded in the Palmarola insular shelf confirms the pristine status of the Pontine area (Ingrassia et al., 2019; Sañé et al., 2021), likely related to reduced fishing effort and absence of large human settlement.

The application of MACS index successfully depicted a wide range of environmental conditions of coralligenous reefs along the Latium continental shelf and allowed for explaining site-specific situations by coupling different kinds of information thanks to the DPSIR approach (Elliott et al., 2017; Enrichetti et al., 2019b). The variable characteristics of the coralligenous basal layer and the patchy distribution of structuring species at Capo Linaro and Costacuti Shoal result in an overall moderated status of benthic communities, obtained through averaging the values of three replicated transects showing different local situations. This evidence combined with an overall moderate-low impact support the moderate-good environmental status of these sites. The poor environmental status for the coralligenous reefs offshore Costacuti Shoal seems to be mainly driven high siltation (either of natural or anthropic origin), as suggested by the low biocoverage and coralline algae coverage and by the occurrence along with *E. cavolini* of erect and massive sponges such as *A. Polypoides*, *S. foetidus* and *S. lamella* that are more tolerant to suspended sediment (Piazzi et al., 2019).

A high environmental status was only reported from the shallower site of Palmarola insular shelf as a result of the almost complete absence of anthropic impacts and the presence of well structured communities. Conversely, in the deeper sites of Palmarola insular shelf structuring species were rarely observed. Here, poor community status and very low

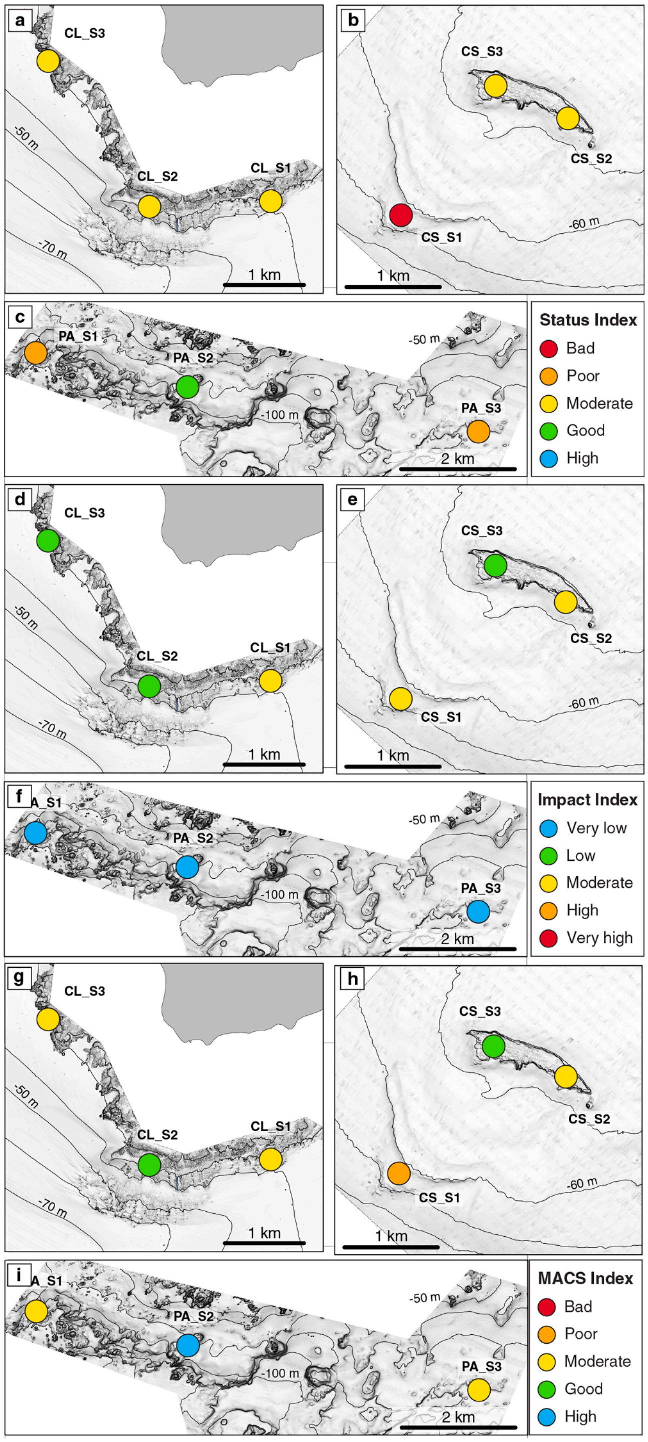


**Fig. 10.** Results of (a-c) Index of Status $I_s$, (d-f) Index of Impact $I_i$ and (g-i) MACS Index for the three investigated area. Refer to SM3 for Indices results.

impact coexist, resulting in an overall moderate environmental status. However, high basal living cover and abundant coralline algae, low siltation levels and the extreme paucity of marine litter, suggest that this area is not affected by natural or anthropic disturbance. The absence of structuring species could be related to natural characteristics of the site, similarly to what observed for the coralligenous assemblages of the western Sardinia (Enrichetti et al., 2019b). In this case, the output of the MACS index should be taken with caution. Overall, a high ecological value can be assumed for the whole Palmarola insular shelf, and more generally for the whole insular shelf of the western Pontine Archipelago where a large variety of coralline algae formations was detected, including both coralligenous reefs and rhodolith beds (Bracchi & Basso, 2012; Martorelli et al., 2012; Ingrassia et al., 2019; Sañé et al., 2021).

## 5. Conclusions

This study showed as the protocol for the coralligenous reefs monitoring adopted by the Latium Region (based on the Marine Strategy Framework Directive), is a relevant tool for the identification and mapping of ecologically relevant benthic habitats across different study areas. This confirms the great advantage of integrating multibeam and side scan sonar data with ROV observations, which allowed the detection of coralligenous reefs based on geomorphological/geoacoustic seafloor characteristics. It also showed that coralligenous reefs distribution and their associated assemblages are highly different in the various investigated sites of the Latium continental shelf. The high variability observed among the explored sites seems to be mainly linked to the different environmental conditions and variable anthropic pressures observed across the investigated areas. Overall, the studied coralligenous reefs host well-structured and diversified benthic communities dominated by suspension feeders, primarily gorgonians species such as *P. clavata*, *E. cavolini*, *E. singularis* and *L. sarmentosa*, but also including anthozoan species of high conservation value such as the red coral *C. rubrum* and the black coral *A. subpinnata*. This result is in agreement with previous studies, confirming the high ecological and biodiversity importance attributed to coralligenous ecosystems.

The application of MACS index allowed to distinguish among a wide range of enviromental conditions of the coralligenous communities. The interpretation of the index outputs should carefully consider the different geological, environmental and oceanographic settings to efficiently discriminate natural patterns from human-induced ones, hence leading to a better interpretation of local situations.

Overall, combining geomorphological analysis and acoustic mapping with qualitative and quantitative information from ROV video footage resulted in a powerful tool for the assessment of the distribution and heterogeneity of coralligenous reefs, their associated communities and the pressures affecting them. This integrated approach could give important information on the extent and diversity of these assemblages helping managers and stakeholders to implement appropriate management measures to guarantee sustainable development of coastal areas and conservation of valuable ecosystems.

## CRediT authorship contribution statement

**M. Pierdomenico:** Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing - original draft. **A. Bonifazi:** Formal analysis, Writing - review & editing. **L. Argenti:** Formal analysis, Investigation, Writing - review & editing. **M. Ingrassia:** Formal analysis, Writing - review & editing. **D. Casalbore:** Visualization, Writing - review & editing. **L. Aguzzi:** Writing - review & editing. **E. Viaggiu:** Writing - review & editing. **M. Le Foche:** Funding acquisition, Project administration. **F.L. Chiocci:** Supervision, Writing - review & editing.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2021.108219.

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